

More efficient biomass gasification via torrefaction

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Abstract

Wood torrefaction is a mild pyrolysis process that improves the fuel properties of wood. At temperatures between 230 and 300 °C, the hemicellulose fraction of the wood decomposes, so that torrefied wood and volatiles are formed. Mass and energy balances for torrefaction experiments at 250 and 300 °C are presented. Advantages of torrefaction as a pre-treatment prior to gasification are demonstrated. Three concepts are compared: air-blown gasification of wood, air-blown gasification of torrefied wood (both at a temperature of 950 °C in a circulating fluidized bed) and oxygen-blown gasification of torrefied wood (at a temperature of 1200 °C in an entrained flow gasifier), all at atmospheric pressure. The overall exergetic efficiency of air-blown gasification of torrefied wood was found to be lower than that of wood, because the volatiles produced in the torrefaction step are not utilized. For the entrained flow gasifier, the volatiles can be introduced into the hot product gas stream as a ‘chemical quench’. The overall efficiency of such a process scheme is comparable to direct gasification of wood, but more exergy is conserved in the product gas (72.6% versus 68.6%). This novel method to improve the efficiency of biomass gasification is promising; therefore, practical demonstration is recommended.

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1. Introduction

Motivated by transition to a more sustainable society, renewable biofuels are expected to replace fossil fuels gradually. Carbon dioxide emissions from using biomass as a fuel are perceived as neutral because carbon dioxide is fixed by photosynthesis in a relatively short period. Nevertheless, it is important to use efficient biomass conversion technologies. For example, the future energy industry could use gasification rather than combustion of biomass. Relatively inefficient combustion of solid fuels in boilers and production of electricity in steam-Rankine cycles was common practice in the 20th century and remains so today. The use of producer gas from wood gasifiers, which could be used in modern devices such as gas turbines, fuel cells or catalytic reactors, is still limited.

Many of the problems in wood gasification are related to the properties of the fuel. Although wood is a clean fuel with low nitrogen, sulphur and ash content, it is thermally unstable, which may lead to formation of

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condensable tars in gasifiers, thus giving problems in down-stream equipment such as choking and blockage of piping (for a recent review, see [1]). Other disadvantages are the low energy density of wood, typically 18 MJ/kg, in combination with its high moisture content as a result of its hygroscopic character, typically around 10 wt% even after drying. Moreover, we have shown in a previous paper [2] that higher gasification efficiencies can be achieved for fuels with low O/C ratios, such as coal, than for fuels with high O/C ratios, such as wood. Firstly, this can be explained due to the high chemical exergy of wood, which is not fully utilized when wood is gasified. Secondly, the optimum temperature for wood gasification is rather low, below 700 °C, but higher gasification temperatures are required in practice, so that wood becomes over-oxidized in the gasifier. Therefore, highly oxygenated biofuels are not ideal fuels for gasifiers from an exergetic point of view. Rather than gasifying these fuels directly, it could be attractive to modify their properties prior to gasification.

A process that lowers the O/C ratio of biomass is known as torrefaction [3–6], which comprises thermal pre-treatment of wood at temperatures from 230 to 300 °C. The main application of torrefied wood is as a renewable fuel for combustion or gasification. In the 1980s, a commercial plant with a capacity of 14,000 ton/year was operated in France, mainly for the production of barbecue fuel [7]. Although torrefied wood was recognized as a clean-burning fuel with little acids in the smoke, commercial success was hampered because it burns much faster than charcoal, which is conventionally used for barbecues. Other uses such as fuel for district heating and for gasifiers were explored. The use of torrefied wood was successfully tested in an air-blown downdraft gasifier: a higher gasification temperature was observed and the product heating value increased from 5.3 to 6.0 MJ/m³ [7]. Novel combinations of torrefaction and gasification have been proposed recently [8]. It is also worth noting that the electricity requirements for size reduction of torrefied wood are 50–85% smaller (depending on torrefaction conditions) in comparison with fresh wood [9]. This facilitates its use in entrained flow, oxygen-blown pressurized gasifiers.

This paper aims to compare gasification of torrefied wood with conventional gasification of wood. The main question is whether wood may be gasified in a more efficient way than direct gasification by using torrefaction as pre-treatment. Attention is focused first on the mass and energy balances of torrefaction. Using these energy balances, several proposed process schemes combining wood torrefaction and gasification are evaluated by process modelling and their efficiencies are compared with conventional direct gasification.

2. Wood torrefaction

2.1. Introduction

Laboratory experiments have been carried out in a small-scale (5–10 g sample) fixed-bed torrefaction reactor placed inside an oven as shown in Fig. 1. The experiments, described in [10], were aimed at recovering and identifying all reaction products, which are present in three phases: a solid product (which retains at least 80% of the energy content of the wood feedstock), condensable gases (such as moisture, acetic acid and other oxygenates) and non-condensable gases (mainly carbon dioxide, carbon monoxide and small amounts of hydrogen and methane). By determining the amount and composition of each phase, it was possible to obtain good quantitative closure of the elemental carbon, hydrogen and oxygen balances.

Various types of biomass have been tested: deciduous wood such as beech and willow and straw and coniferous wood such as larch. Deciduous wood has been found to be much more reactive than coniferous wood under torrefaction conditions. This may be explained because the hemicellulose fraction in deciduous wood contains mainly xylan, which is much more reactive than the mannan found in coniferous wood. Important thermal decomposition reactions in torrefaction processes are dehydration, decarboxylation and deacetylation of the xylan-containing hemicellulose polymers. Results are therefore given mainly for beech and willow, of which the thermal behaviour is very similar.

2.2. Properties of torrefied wood

Fig. 2 compares the elemental composition of fresh beech wood and the torrefied product. The latter was obtained after heating beech wood from 200 °C (around this temperature, wood starts to decompose) to temperatures between 220 and 280 °C in 3–12 min, whereafter the temperature is kept constant for 30 min. The



Fig. 1. Bench-scale experimental set-up for wood torrefaction.

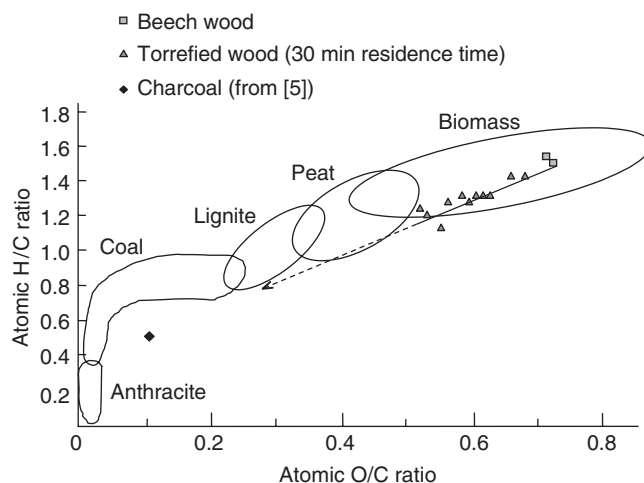


Fig. 2. Composition of beech wood and torrefied beech wood (obtained at temperatures from 220 to 280 °C) in van Krevelen diagram.

triangle points closest to the original beech wood were measured at the lower temperatures (220–230 °C) and those furthest away at the higher temperatures (270–280 °C). Due to removal of water and carbon dioxide, the composition of the torrefied product has a lower O/C and H/C ratio. The product composition is still very different from charcoal, which requires much higher temperatures to produce. Torrefied wood has a brown colour and retains 70–90% of the weight of the biomass feed. The properties of torrefied wood were found to be in between wood and coal. Compared to the original wood, torrefaction decreases the content of volatiles from ca. 80% to 60–75% and the moisture content from typically 10% to 0–3%, whereas the heating value increases by 5–25%. The properties of torrefied wood depend on the type of wood used, and the reaction temperature and residence time that is applied; the required reaction time decreases with temperature and may be calculated from a kinetic model, such as the one described in [10].

Table 1
Composition of wood and torrefied wood (for willow)

	Wood	Torrefied wood (250 °C, 30 min)	Torrefied wood (300 °C, 10 min)
Carbon	47.2%	51.3%	55.8%
Hydrogen	6.1%	5.9%	5.6%
Oxygen	45.1%	40.9%	36.2%
Nitrogen	0.3%	0.4%	0.5%
Ash	1.3%	1.5%	1.9%
LHV(MJ/kg)	17.6	19.4	21.0

Table 1 presents the composition of wood and torrefied wood, obtained by two experiments using willow: at a reaction temperature of 250 °C and reaction time of 30 min, and 300 °C and 10 min, respectively. Reaction times exclude a heating time (from 200 °C to the reaction temperature) of 8.5 min and 17 min, respectively. As a result of the torrefaction process, the lower heating value of the wood increases from 17.6 to 19.4 and 21.0 MJ/kg, respectively.

Torrefaction has a large effect on the strength of the cell wall in wood material. This is most probably caused by decomposition of hemicellulose, the main fraction reacting in the temperature range of torrefaction. The polysaccharides in woody plant cell walls are physically aggregated into very long strands known as microfibrils. These microfibrils are essentially a core of crystalline cellulose encased in a shell of hemicellulose [11]. The microfibrils are enclosed in a continuous system of amorphous lignin. By decomposing hemicellulose in the torrefaction process, the orientation of the microfibrils in the lignin matrix may change, which influences the viscoelastic properties of the wood. Furthermore, depolymerization of cellulose and thermal softening of lignin may play a role.

2.3. Mass and energy balances

Table 2 presents mass and energy balances for the experiments of Table 1. At higher temperature, more volatiles are formed so that the mass yield for the two cases is 87% and 67%, respectively. The main volatile product is steam, which is formed by dehydration reactions of the wood. Many organic products are formed, mainly acetic acid, but also furfural, formic acid, methanol, lactic acid, phenol and others. The gaseous product typically consists of 80% carbon dioxide and 20% carbon monoxide, with small amounts of hydrogen and methane.

Fig. 3 shows the overall mass and energy balances for the two experiments. The energy balance shows that 95% and 79% of the respective energy input (the lower heating value of the wood plus heat supplied to the process) is retained in the solid product. These values have been determined by an ASTM method using an adiabatic bomb calorimeter, which has an inaccuracy of approximately 240 kJ/kg. This complicates the determination of the net reaction enthalpy, which is calculated from the difference of the in- and outgoing process streams. To determine the reaction enthalpy more accurately, other experiments are required, e.g. by differential scanning calorimetry in combination with thermogravimetry. In practice, wood always contains a certain amount of moisture, typically 7–10% after drying, so that heat is required to evaporate moisture and the overall process is certainly endothermic.

3. Wood torrefaction combined with gasification

3.1. Process options

The main idea behind combining biomass torrefaction and gasification is as follows: in gasifiers, biofuels such as wood are converted into combustible product gas and heat. This heat is normally recovered in the form of medium- or high-pressure steam, which may be exported and/or used for electricity generation. Alternatively, steam can be partially used to supply the heat for the torrefaction process. Bone-dry torrefied

Table 2

Mass and energy balances for torrefaction of (dry) willow at a temperature of 250 °C (reaction time of 30 min) and 300 °C (reaction time of 30 min)

	Torrefaction (250 °C, 30 min)			Torrefaction (300 °C, 10 min)		
	Mass (kg/kg)	LHV (kJ/kg)	Sensible heat (kJ/kg)	Mass (kg/kg)	LHV (kJ/kg)	Sensible heat (kJ/kg)
<i>Torrefied wood</i>						
Org. material	0.859	16883	202	0.655	14024	189
Ash	0.013			0.013		
Total	0.872			0.668		
<i>Volatiles</i>						
Steam	0.057	0	24	0.066	0	35
Acetic acid	0.021	300	6	0.072	1001	28
Other organics	0.018	258	6	0.142	2280	59
Carbon dioxide	0.029	0	6	0.040	0	11
Carbon monoxide	0.003	30	1	0.012	121	3
Hydrogen	Trace	1	0	Trace	1	0
Methane	Negl.	0	0	Trace	2	0
Total	0.128	589	43	0.332	3405	136

Data per kg of wood input.

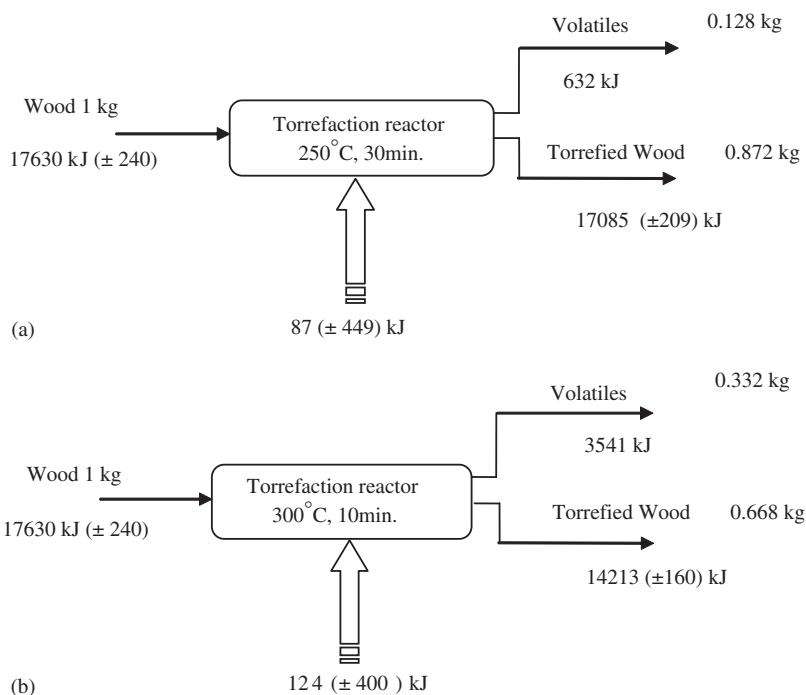


Fig. 3. Overall mass and energy balances for torrefaction of (dry) willow at temperature and reaction time of (a) 250 °C and 30 min (b) 300 °C and 10 min.

wood with increased heating value is formed, which is subsequently gasified. In this way, advantage is taken of the high reactivity of wood (which is related to its relatively high chemical exergy), and part of the sensible heat of gasification product gas is put 'back into' the gasifier. The design of a torrefaction reactor, which is placed in front of the gasifier, is similar to a drier. In this case, indirect heat transfer based on heat conduction is selected, which allows precise temperature control. A steam tube drier, possibly with rotation to promote contact between the solid particles and hot steam tubes, may be used.

The concept of torrefaction aided gasification is similar to two-stage pyrolysis–gasification, but differs in two aspects. Firstly, the temperature of the torrefaction stage is carefully controlled at or below 300 °C in order to minimize pyrolysis of cellulose and avoid tar formation. Secondly, the heat requirements for torrefaction are smaller than those for pyrolysis at higher temperatures. Therefore, instead of taking heat from the gasifier itself (e.g. by recirculation of hot sand), sufficient heat can be taken from the gasifier product gas.

Fig. 4 shows process options for gasification of wood or torrefied wood.

- Conventional biomass gasification in a circulating fluidized bed (CFB) is shown in Fig. 4a. Alternatively, bubbling-fluidized beds and (on a small scale) moving-bed gasifiers may be applied. The operating temperature in CFB gasifiers is below 1000 °C, in order to avoid problems with ash softening and melting, and operating pressure is mostly atmospheric. Air is generally used as a gasifying medium.
- In Fig. 4b, the solid product of the torrefaction reactor is fed to an air-blown CFB gasifier. The volatile product is not used in the process and regarded as a waste stream. To dispose of this waste stream, acidic water can be condensed and sent to a biological wastewater treatment plant, while the non-condensable gases could be (catalytically) combusted.
- Fig. 4c shows gasification of torrefied wood in an oxygen-blown entrained flow (EF) gasifier. Prior to its introduction into the gasifier, torrefied wood is pulverized to a particle size of 100 µm, which behaves as a Geldart A powder suitable for fast fluidization [9]. The torrefied wood is gasified at a very high temperature,

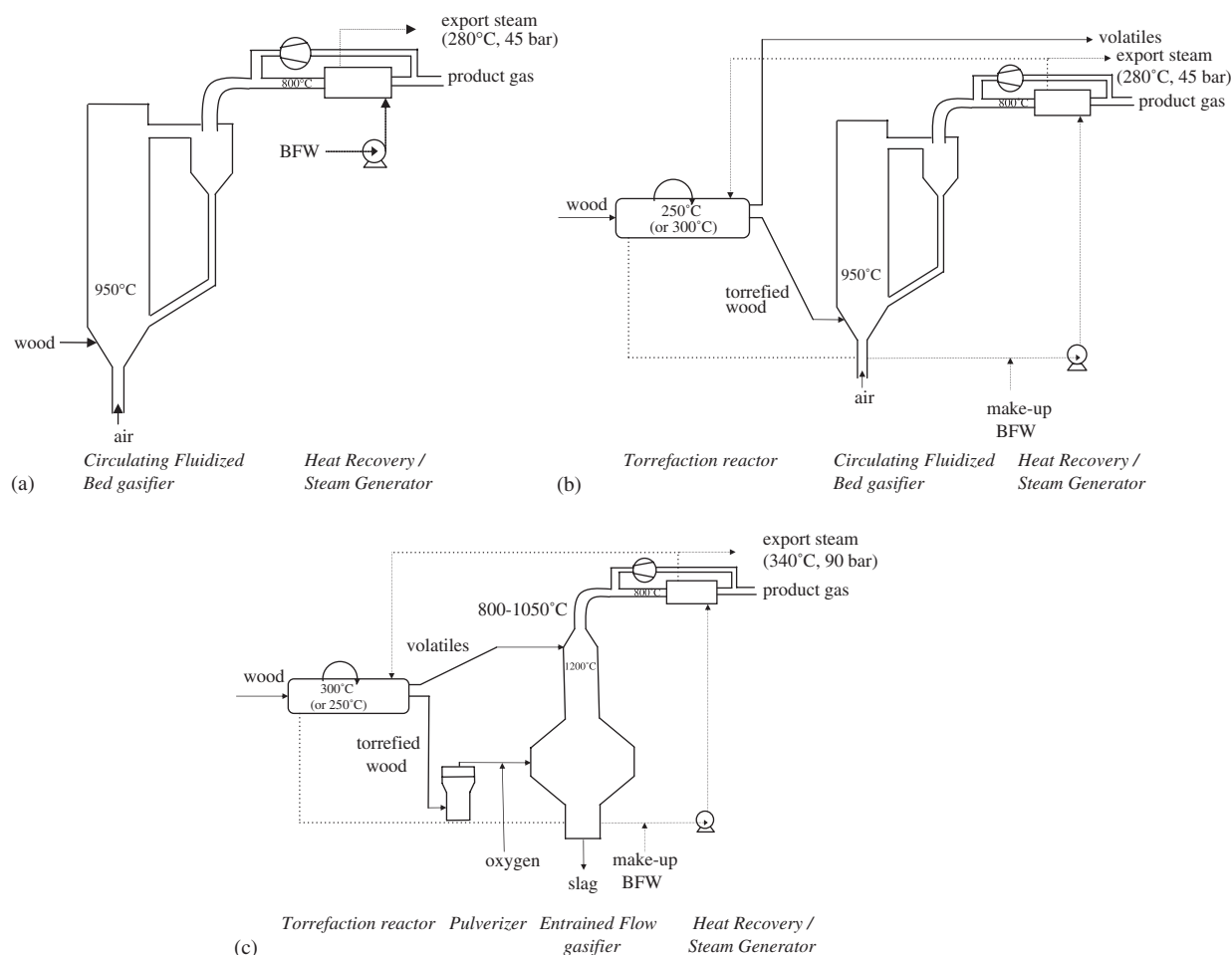


Fig. 4. Gasification process schemes: (a) CFB gasification of wood (air-blown); (b) wood torrefaction and CFB gasification of torrefied wood (air-blown) and (c) wood torrefaction integrated with EF gasification of torrefied wood (oxygen-blown).

with flame temperatures up to 1700 °C and gas outlet temperatures ranging from 1000–1400 °C. The hot gas leaving the gasifier is normally physically quenched, e.g. with cold recycle gas, but it is also possible to use the torrefaction volatiles in order to induce a ‘chemical quench’ [12]. Due to the high temperature, the thermally unstable volatiles from the torrefaction step will decompose into carbon monoxide and hydrogen and provide a cooling effect so that the temperature drops by 100–400 °C (depending on the amount of volatiles that are introduced, which in turns depends on the torrefaction conditions). This method avoids the loss of organic material from the torrefaction reactor, because all product streams are effectively used in the gasification system and contribute to the production of synthesis gas.

3.2. Process modelling

The three process flow sheets have been simulated in Aspen Plus, version 11. The model is based on dry wood as a fuel, because the main interest was to check the effect of modifying the chemical composition prior to gasification, thereby excluding the effect of drying. The model is based on the following input parameters:

- The wood feedstock is initially reduced in size to particle diameters of a few centimetres, both for use in a CFB gasifier and in a torrefaction reactor. Since the requirements of the different options are similar and the electricity required is expected to be relatively small, this term is not taken into account.
- The mass and energy balances of the torrefaction cases at 250 and 300 °C were used as an input for the simulation.
- The required power for pulverizing torrefied wood (at room temperature) to a particle size of 100 µm is approximately 10–20 kWe/MWth [9]. Values of 12 and 10 kWe/MWth were applied for torrefaction at 250 and 300 °C, respectively. These are conservative estimates because the energy required for size reduction may be even less if torrefied wood is pulverized while it is hot.
- For cryogenic air separation, electricity requirement of 380 kWh/ton oxygen is used [13].
- The gasifier has been modelled using an equilibrium model. This indicates the maximum thermodynamic efficiency that may be achieved in the three processes. Operating temperatures of 950 and 1200 °C were assumed for CFB and EF gasification, respectively, whereas operating pressure was atmospheric in all cases.
- At a gasification temperature of 1200 °C, melting of ash and formation of a slag is unlikely (although indicated in Fig. 4c). Therefore, the heat of fusion of the ash is not considered.
- The hot product gases from the gasifier are physically quenched with cold product gas (after a possible chemical quench) to a temperature of 800 °C, as is common in many gasifiers such as the high-temperature coal gasifier developed by Shell. This allows for relatively cheap construction materials in the Heat Recovery/Steam Generator (HRSG). Steam produced in this unit is partially used to provide heat for the torrefaction process and partially exported. The pressure of the steam generated in the HRSG is tailored for controlling the torrefaction temperature: 45 bar for torrefaction at 250 °C and 90 bar for torrefaction at 300 °C.

3.3. Energy and exergy calculations

Exergy balances were set up for the different process schemes as shown in Fig. 4. As an example, the exergy balance of the scheme in Fig. 4c has the following form:

$$\varepsilon_{\text{in}} = \varepsilon_{\text{out}} + I, \quad (1)$$

$$\begin{aligned} \varepsilon_{\text{wood}} + \varepsilon_{\text{air}} = & \varepsilon_{\text{product gas}} + \varepsilon_{\text{steam}} + \varepsilon_{\text{N}_2} \\ & - \frac{E_{\text{air separation}} + E_{\text{size reduction}} + E_{\text{gasification}}}{\Psi_{\text{electricity generation}}} + I_{\text{torrefaction}} \\ & + I_{\text{size reduction}} + I_{\text{air separation}} + I_{\text{gasification}}. \end{aligned} \quad (2)$$

In these equations, $\varepsilon_{\text{wood}}$, ε_{air} , $\varepsilon_{\text{product gas}}$, $\varepsilon_{\text{steam}}$ and ε_{N_2} represent the exergy of wood, air, product gas, produced steam and nitrogen, $E_{\text{air separation}}$ the electricity required for cryogenic air separation, $E_{\text{size reduction}}$ the electricity required for size reduction of torrefied wood, $E_{\text{gasification}}$ the electricity for recycling cold synthesis gas for quenching the product gas of the gasifier, Ψ the efficiency for generating electricity from product gas (estimated at 50%, e.g. a combined cycle can be applied), and I the irreversibility with the subscript denoting the unit operation. The electricity for the boiler feed water (BFW) pump may be neglected. Thermodynamic data of all components were obtained from Szargut et al. [14]. The chemical exergy of wood was calculated from its lower heating value, whereas the chemical exergy of air is zero because it is a component of the environmental reference system and the chemical exergy of nitrogen may be neglected.

To compare the gasification efficiencies of the various process options, the exergetic efficiency is used. The overall efficiency based on the exergy of product gas and steam relative to the exergy of the wood fuel is defined as

$$\Psi_{\text{overall}} = \varepsilon_{\text{product gas}} + \varepsilon_{\text{steam}} - (E_{\text{air separation}} + E_{\text{size reduction}} + E_{\text{gasification}} / \Psi_{\text{electricity generation}}) / \varepsilon_{\text{wood}}. \quad (3)$$

3.4. Results

Figs. 5a and b show the overall gasification efficiencies as a function of gasification temperature for the various process options: air-blown CFB gasification of wood (Fig. 4a) and torrefied wood (Fig. 4b), for torrefaction at 250 and 300 °C, respectively, and oxygen-blown integrated EF gasification of torrefied wood (Fig. 4c), for torrefaction at 250 and 300 °C, respectively. The overall efficiency of air-blown CFB gasification is lower for torrefied wood than for wood, especially at a high torrefaction temperature when a lot of energy is contained in the volatiles, which are not used in the process. Compared to air-blown CFB gasification of wood, the overall efficiency for oxygen-blown integrated EF gasification of torrefied wood is slightly lower if torrefied wood is produced at 250 °C, but quite comparable if torrefied wood is produced at 300 °C. Several typical operating temperatures (I, IIa, IIb, IIIa and IIIb) have been indicated in Fig. 5, for which more detail is given below. Detailed exergy balances at the indicated operating temperatures are presented in Table 3.

Fig. 6 splits out the overall efficiency into several contributions: chemical exergy of product gas, physical exergy of product gas (at the outlet temperature of the HRSG) and exergy of steam. The highest amount of chemical exergy conserved is observed for case IIIb (torrefaction at 300 °C integrated with gasification at 1200 °C). For this option, little steam is generated due to the smaller gas volume when oxygen is used as gasifying medium and most of this steam is required for torrefaction.

In order to understand the observed trends, the process losses are analyzed and shown in Fig. 7. These process losses consist of internal losses (irreversibilities) and external losses. The external losses consist of volatiles lost as a waste stream (for CFB gasification of torrefied wood) and of hot ash emitted from the gasifier. The latter term was found to be very small and is therefore not shown. From Fig. 7, it becomes clear that the exergy contained in the torrefaction volatiles can be substantial, especially at 300 °C, which explains why the concept of CFB gasification of torrefied wood has a lower efficiency than for gasification of wood. In cases IIIa and IIIb, in which the volatiles from wood torrefaction are used to quench the gasifier product gas, this external loss is avoided. Internal losses occur in all unit operations: torrefaction, gasification, and air separation (4.7% and 3.8% for gasification of torrefied wood prepared at 250 and 300 °C, respectively) and size reduction (3.0% and 2.5%, respectively). The internal losses occur mostly in the gasifier; these are reduced when torrefied wood is fed to the gasifier instead of wood. This might have been expected because the amount of solid material that needs to be gasified is smaller. However, even the combined irreversibilities for torrefaction and gasification are smaller than those for direct gasification. This can be understood by realizing that torrefaction (hemicellulose decomposition) conventionally takes place in the gasifier itself. To this end, heat from the oxidation zone in the gasifier is released at high temperature and downgraded to a lower temperature. If the torrefaction step is performed outside the gasifier, a lower-quality heat can be used, i.e. steam produced from cooling the gasification product gas, which is beneficial.

The triangular CHO-diagram in Fig. 8 presents another reason for the increased gasification efficiency of torrefied wood. In this diagram, the so-called carbon boundary line (see e.g. [15]) is shown at a temperature of

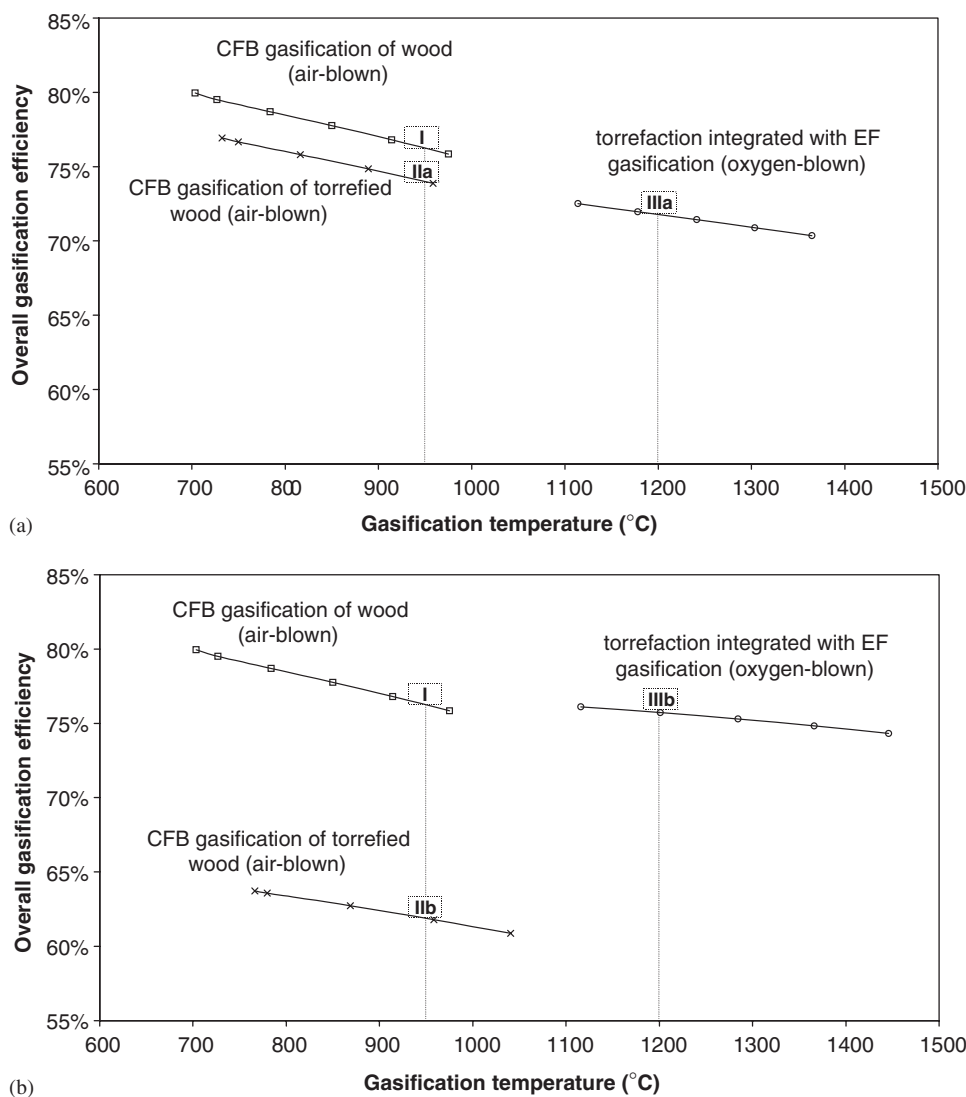


Fig. 5. Overall gasification efficiency at varying gasification temperature for different process schemes.

950 °C. This line has to be crossed in order to avoid formation of solid carbon. The thermodynamic optimum is on the carbon boundary line, where exactly enough oxygen is added to achieve complete gasification. Considering gasification of wood at 950 °C, there is a considerable amount of over-oxidation, which negatively influences the gasification efficiency. If wood is modified by torrefaction, its composition becomes more favourable so that it is over-oxidized less in the gasifier.

3.5. Discussion

In several input parameters for the process models, such as the torrefaction energy balances, inaccuracies exist so that the results presented in Figs. 5 and 6 do not provide firm evidence that one process option is more efficient than the other. Nevertheless, oxygen-blown EF gasification of torrefied wood seems to be an attractive option to conserve the chemical exergy of wood in the product gas maximally, at a high gasification temperature. Direct gasification of wood at this temperature would have a much lower efficiency.

Table 3

Exergy balances for gasification process schemes (as in Fig. 4), in kJ

	I	IIa	IIb	IIIa	IIIb
Torrefaction temperature	n/a	250 °C	300 °C	250 °C	300 °C
Gasification temperature	950 °C	950 °C	950 °C	1200 °C	1200 °C
<i>Torrefaction</i>					
IN					
Wood	n/a	20023	20023	20023	20023
Reaction heat (steam)		38	60	38	60
OUT					
Torrefied wood		18964	15564	18964	15564
Volatiles		693 ^a	3730 ^a	693	3730
<i>I, torrefaction</i>		405	789	405	789
<i>Size reduction</i>					
<i>I, size reduction^b</i>	n/a	n/a	n/a	601	501
<i>Air separation</i>					
IN					
Air				0	0
Electricity ^b	n/a	n/a	n/a	973	807
OUT					
Oxygen				46	38
<i>I, air separation</i>				927	769
<i>Gasification</i>					
IN					
Wood or Torrefied Wood	20023	18964	15564	18964	15564
Volatiles	n/a	n/a	n/a	693	3730
Air or oxygen	0	0	0	46	38
Electricity	60	55	55	63	0
OUT					
Product gas	14064	13765	11574	15178	16050
Steam	1263	1145	932	871	480
Ash	5	5	5	5	5
<i>I, gasification</i>	4753	4105	3108	3713	2798

Data per kg of wood input.

^aExternal loss.^bIncludes irreversibilities for generation of the required electricity from product gas.

There are several advantages for oxygen-blown EF gasification of torrefied wood, which should be mentioned. Firstly, the process simulations were based on dry wood, but wood always contains some moisture, which is physically adsorbed. By decomposing the hemicellulose fraction in a torrefaction reactor, moisture present will evaporate so that always a bone-dry solid product is gasified. In CFB gasification of wood, the efficiency drops quickly with moisture content of the fuel. For example, if wood is used with a moisture content of 8.6%, the efficiency drops by 1.5 percentage points compared to only 0.7 percentage points for torrefaction (at 250 °C) integrated with EF gasification. Secondly, the gasification reactions in the gasifier were assumed to reach chemical equilibrium. However, at the operating temperature of CFB gasifiers, these reactions are too slow and do not contribute sufficiently to the carbon conversion [16]. Typical carbon conversions are around 90%, whereas at higher gasification temperatures of EF gasifiers, almost complete conversion can be expected. However, this has yet to be verified experimentally. Thirdly, the possibility exists for operating the EF gasifier at elevated pressure, which is beneficial for many downstream operations such as gas turbines and catalytic reactors for production of hydrogen, methanol, dimethylether or Fischer–Tropsch hydrocarbons. It would then also be attractive to operate the torrefaction reactor at elevated pressure, but this has not yet been tested experimentally either. Finally, the catalytic reactors mentioned also benefit from the

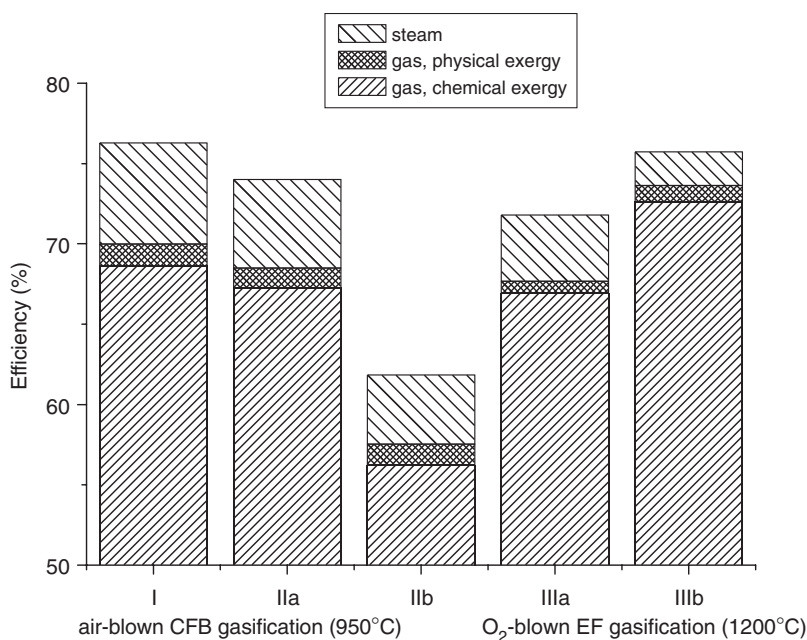


Fig. 6. Exergetic efficiency of different process schemes.

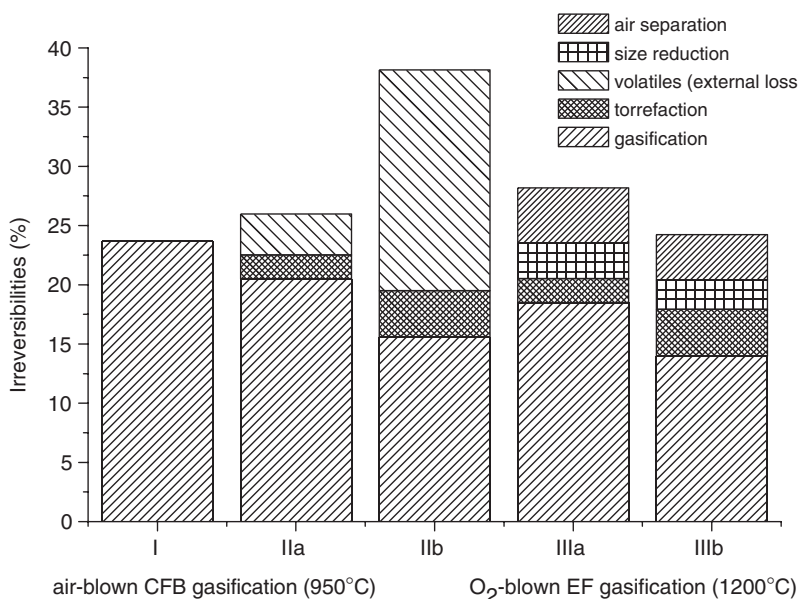


Fig. 7. Thermodynamic losses of different process options.

fact that the product gas from high-temperature gasifiers contains very little methane, which is inert and passes these reactors unconverted.

Several studies, e.g. by Ciferno and Marano [17], have identified high-temperature gasification of biomass as a promising option. We regard torrefaction as an enabling pre-treatment technology, which solves two problems simultaneously: the high-energy requirements for size reduction as well as the low heating value and the high moisture content of untreated wood.

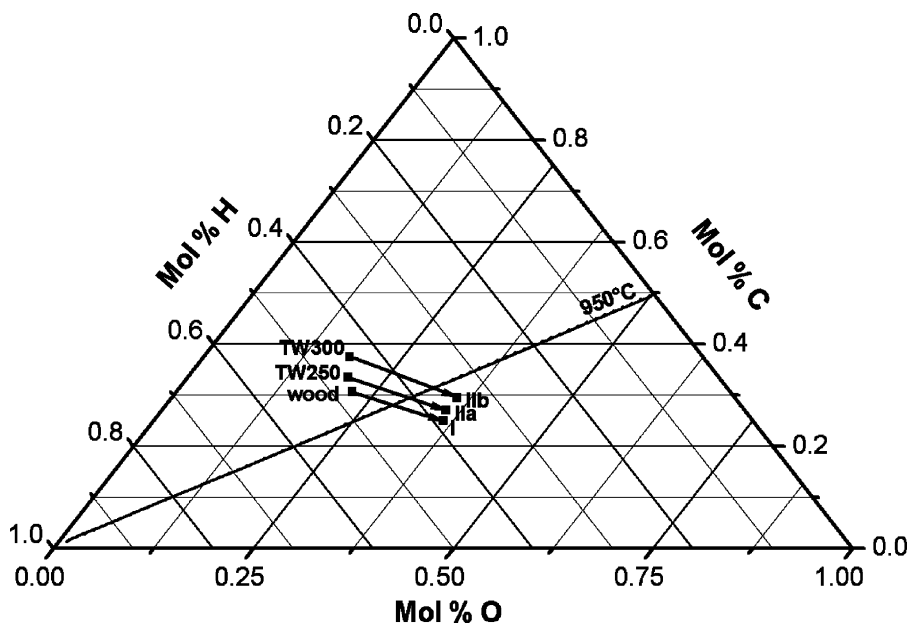


Fig. 8. Gasification of wood and torrefied wood (TW; produced at 250 and 300 °C) at a temperature of 950 °C illustrated in a CHO-diagram.

4. Conclusions and recommendations

Although wood is a clean and renewable fuel which, compared to coal, contains little ash, sulphur and nitrogen, it is not an ideal fuel for gasifiers. Its optimum gasification temperature is rather low (below 700 °C) due to the high O/C ratio of the fuel and high moisture content. As a result, wood is generally over-oxidized in gasifiers leading to thermodynamic losses. This paper has shown that it is possible to reduce these thermodynamic losses by prior thermal pre-treatment in the range of 250–300 °C, i.e. wood torrefaction. If the heat produced in the gasifier is used to drive the wood torrefaction reactions, then the chemical exergy preserved in the product gas has been shown to increase provided that both torrefied wood and volatiles are introduced into the gasification process. This is a novel, promising method to achieve more efficient gasification of wood. It is thus recommended to test this integrated process in practice and also to consider the effect of a torrefaction pre-treatment step on process economics. An exergo-economic study could be considered to determine the final value of the synthesis gas product.

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